ATMOSPHERIC PRE-CORRECTED DIFFERENTIAL ABSORPTION TECHNIQUES TO RETRIEVE COLUMNAR WATER VAPOR: THEORY AND SIMULATIONS

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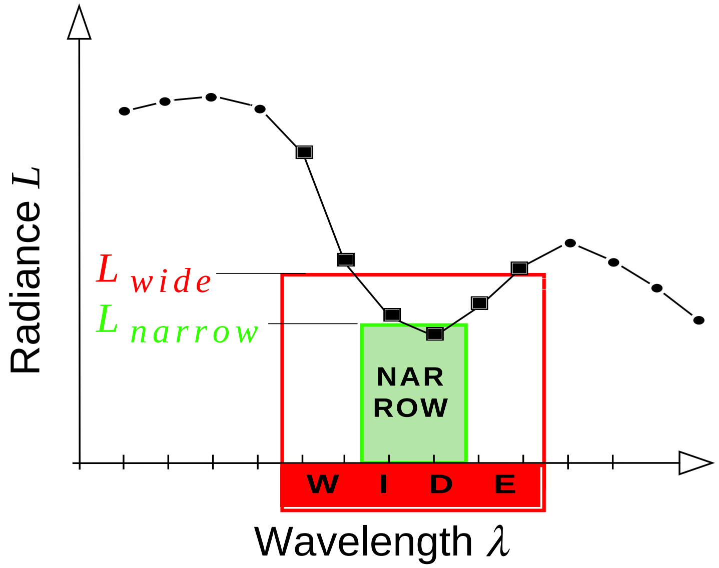
EXISTING WATER VAPOR RETRIEVAL METHODS

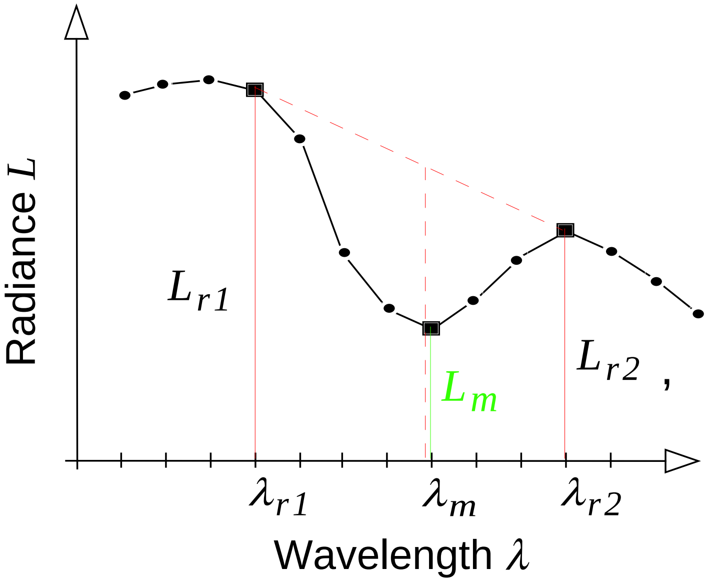
1. Differential absorption techniques based on:
    - (a) Narrow-Wide (N/W) ratio between overlapping spectrally wide and narrow channels (Frouin et al, 1990)
    - (b) Continuum Interpolated Band Ratio (CIBR) between a measurement channel and the weighted sum of two reference channels (Green et al, 1989, Bruegge et al, 1990, Gao and Goetz, 1990a, and Carrére and Conel, 1993)
2. Non-linear fitting techniques which are based on spectral radiative transfer calculations (Gao and Goetz, 1990b, Green et al, 1993).

Narrow/Wide


Radiance L
L_{wide}
L_{narrow}
NAR ROW
W I D E
Wavelength λ

$$R_{N/W} = \frac{L_{narrow}}{L_{wide}}$$

Continuum Interpolated Band Ratio


Radiance L
L_{r1}
L_m
L_{r2} ,
λ_{r1}
λ_m
λ_{r2}
Wavelength λ

$$R_{CIBR} = \frac{L_m}{\omega_{r1} \cdot L_{r1} + \omega_{r2} \cdot L_{r2}}$$

$$\omega_{r1} = \frac{\lambda_{r2} - \lambda_m}{\lambda_{r2} - \lambda_{r1}}$$

$$\omega_{r2} = \frac{\lambda_{r1} - \lambda_m}{\lambda_{r2} - \lambda_{r1}}$$

ATMOSPHERIC PRE-CORRECTED DIFFERENTIAL ABSORPTION

DERIVATION:

STEP 1: Duntley in 1948 expressed the radiance L measured in channel i by a sensor as:

$$L_i \ = \ \rho_{g,i}\frac{E_i}{\pi}T_i \ + \ L_{h,i}(1 - T_i^*) = L_{g,i}T_{0,i}T_i(PW) + L_{p,i}(PW), \qquad (1)$$

where

$\rho_{g,i}$ is the ground reflectance, PW is the precipitable water in $[gcm^{-1}]$,

E_i is the solar irradiance, T_i is the total transmission,

$L_{h,i}$ is the radiance one would measure in a plane parallel atmosphere in horizontal direction,

T_i^* is a special transmission term (Duntley assumes: $T_i = T_i^*$),

$T_{0,i}$ transmission without any water vapor and $L_{p,i}$ is the path radiance.

STEP 2: Linear interpolation of radiance in measurement (m) channel:

$$L_m(PW) = [w_{r1} L_{g,r1} T_{0,r1} + w_{r2} L_{g,r2} T_{0,r2}] T_m(PW) + L_{p,m}(PW), \qquad (2)$$

where

$$w_{r1} = \frac{\lambda_{r2} - \lambda_m}{\lambda_{r2} - \lambda_{r1}} \quad \text{and} \quad w_{r2} = \frac{\lambda_m - \lambda_{r1}}{\lambda_{r2} - \lambda_{r1}}. \qquad (3)$$

STEP 3: Solve for $T_m(PW)$:

$$T_m(PW) = \frac{L_m - L_{p,m}(PW)}{w_{r1}(L_{r1} - L_{p,r1}) + w_{r2}(L_{r2} - L_{p,r2})} \qquad (4)$$

STEP 4: Approximate $L_{p,m}$ with polynomial of second (or higher) order:

$$L_{p,m}(PW) = aPW^2 + bPW + c + L_{\mathrm{adj,m}}, \qquad (5)$$

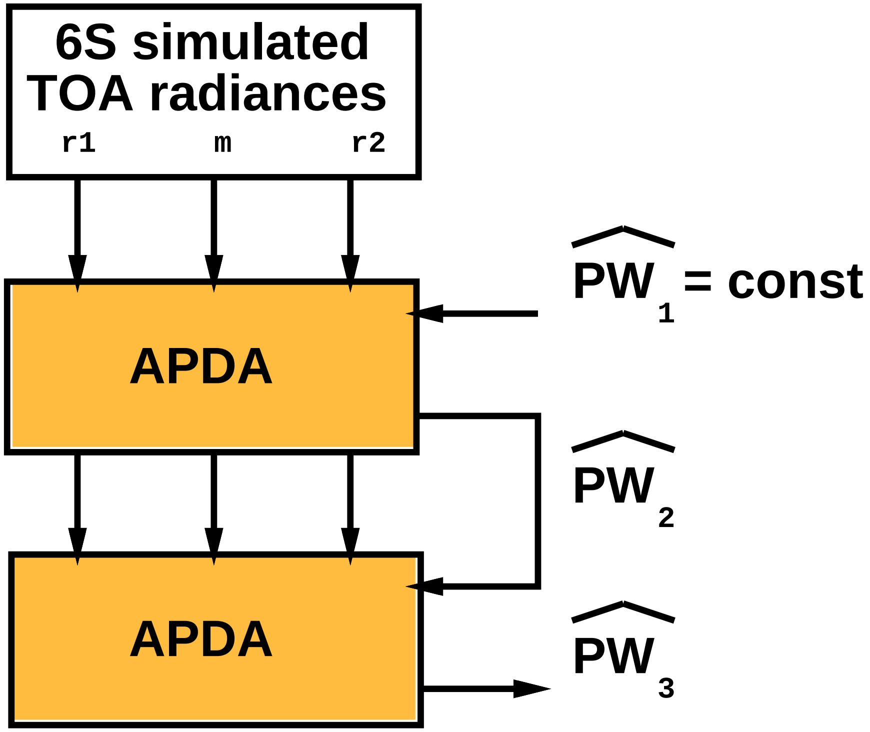
APDA Ratio:

$$R_{APDA}(PW) = \frac{L_m - (aPW^2 + bPW + c)}{w_{r1}(L_{r1} - L_{p,r1}) + w_{r2}(L_{r2} - L_{p,r2})}. \qquad (6)$$

ITERATIVE APDA SOLUTION

GOAL: Find precipitable water $PW(j,k)$ for pixel (j,k):

1. Use a radiative transfer code (6S or MODTRAN 3) to compute the path radiance $L_{p,m}$ for an average reflectance background (e.g. $\rho_{g,i} = 0.4$) as a function of water content and fit a polynomial (eq.(5)) to $L_{p,r1}$ and $L_{p,r2}$ for a zero reflectance backgrounds. Note that the path radiances $L_{p,r1}$ and $L_{p,r2}$ are assumed to be independent of PW.
2. Use a spectral radiative transfer code (6S or MODTRAN 3) to compute the total radiance over a zero reflectance background as a function of water vapor PW. Since the ratio $R_{APDA}(PW)$ decreases monotonically with increasing water vapor a spline interpolation is used to go from a given ratio to columnar water vapor.
3. Assume as a starting value an average water vapor $\overline{PW}_1$ for the whole scene.



6S simulated TOA radiances

r1 m r2

APDA

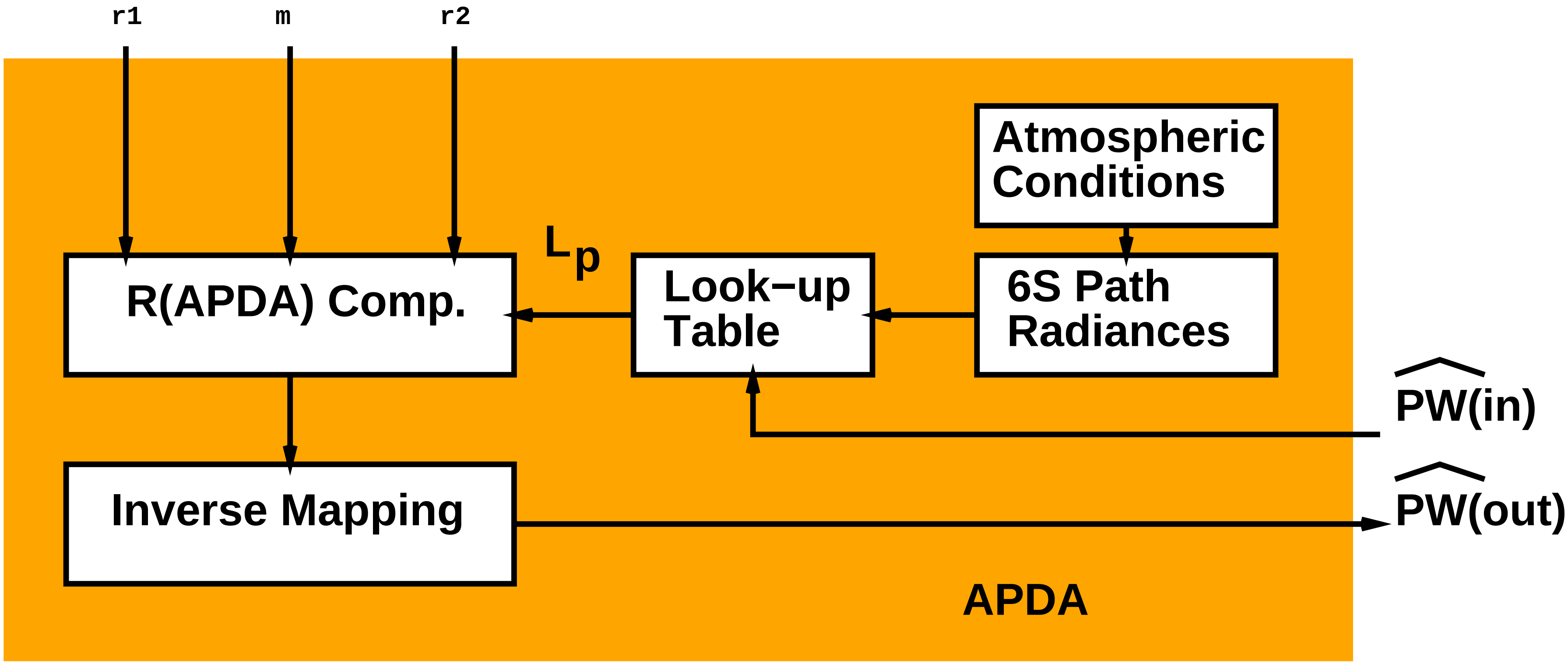
$\widehat{PW}_1$ = const

$\widehat{PW}_2$

APDA

$\widehat{PW}_3$

General schematic for iterative APDA on the 6S simulated TOA radiance data set.



r1

m

r2

R(APDA) Comp.

L_p

Look−up Table

Atmospheric Conditions

6S Path Radiances

$\widehat{\text{PW(in)}}$

Inverse Mapping

$\widehat{\text{PW(out)}}$

APDA

Detailed schematic for APDA retrieval.

4. Compute $R_{APDA}(j,k)$ for each pixel (j,k) using equation (6) and use the cubic spline interpolation to get a second estimate $PW_2(j,k)$ for the columnar water vapor.
5. Substitute $PW_2(j,k)$ for PW the right side of equation (6) to get a better atmospheric pre-corrected differential absorption ratio $R_{APDA}(j,k)$.
6. Determine from the second ratio $R_{APDA}(j,k)$ a third water vapor amount $PW_3(j,k)$ using the cubic spline interpolation.
7. Repeat steps 5 and 6 a few times or until $|PW_i(j,k) - PW_{i-1}(j,k)| \leq 10^{-4}$.

CONTINUUM INTERPOLATED BAND RATIO (CIBR)

DEFINITION:

$$R_{CIBR} = \frac{L_m}{w_{r1}L_{r1} + w_{r2}L_{r2}} \tag{7}$$

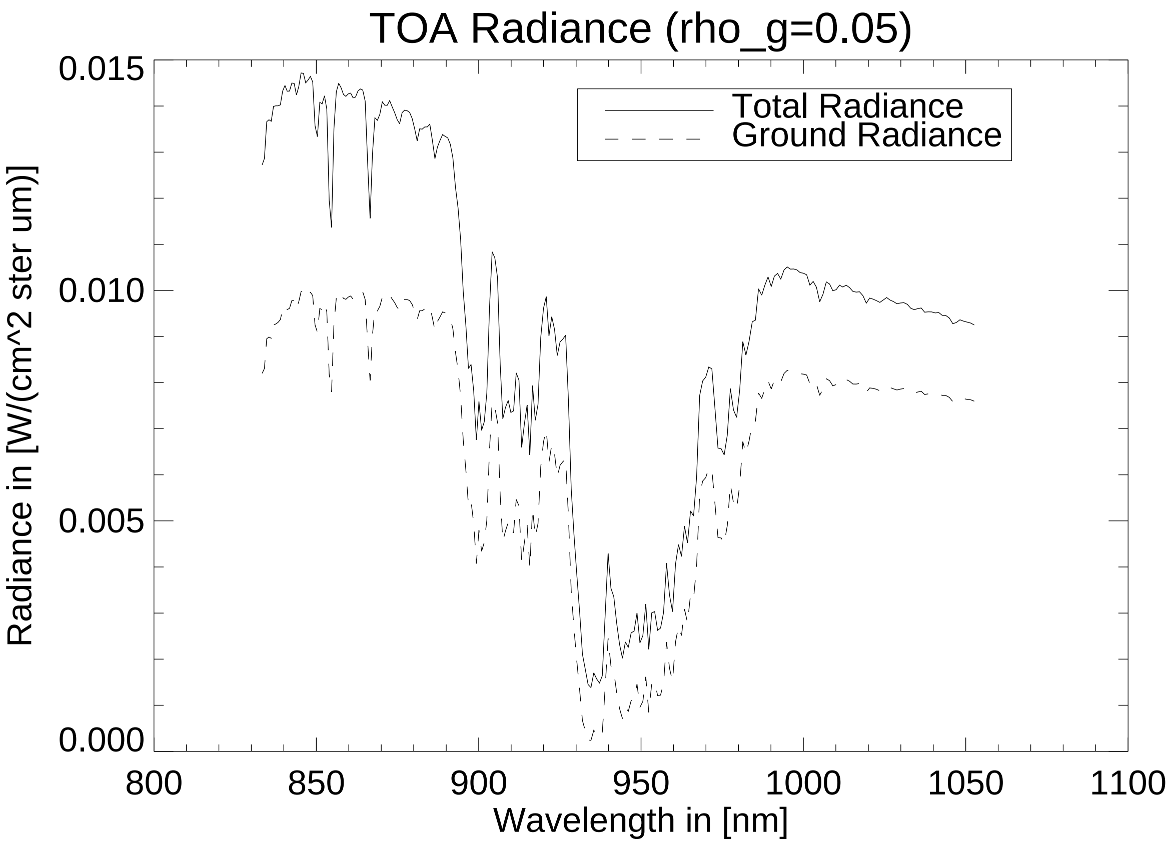
NOTES:

- The CIBR assumes that the underlying surface reflectance is linear over the range of wavelengths of interest.
- The CIBR works for highly reflective backgrounds (e.g. playas)
- Influence of path radiance for dark targets has been recognized since 1989 but has not been explicitly treated (except in non-linear fitting methods).

DARK TARGET CIBR:

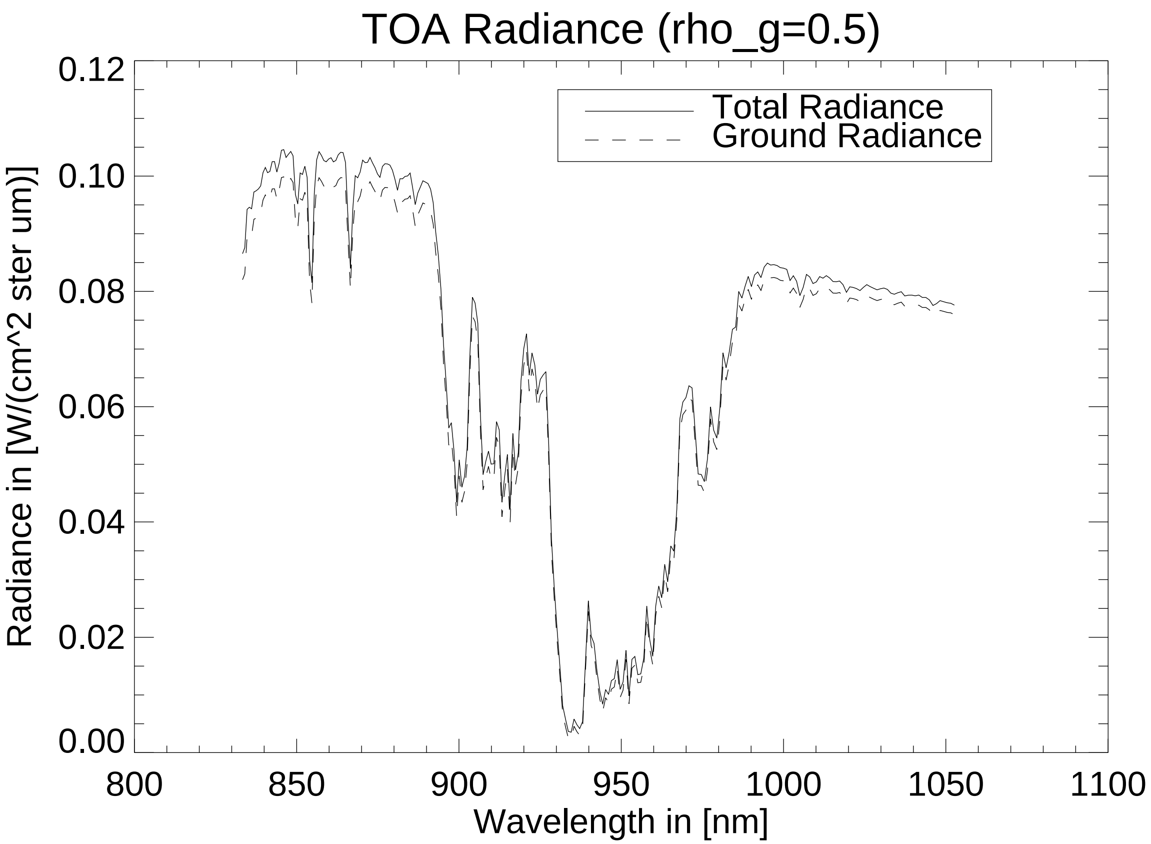
$$R_{CIBR}(\rho_{g,i} \approx 0.) \;\approx\; \frac{L_{p,m}(PW)}{w_{r1}L_{p,r1} + w_{r2}L_{p,r2}}. \tag{8}$$

Thus $R_{CIBR} \approx L_{p,m}(PW) = L_{h,m}[1 - T^{*}_{m}(PW)] \neq T_{m}(PW)$.



BRIGHT TARGET CIBR:

$$R_{CIBR}(\rho_{g,i} \approx 1.) \;\approx\; Const\, T_m(PW). \tag{9}$$



COMPARISON CIBR AND APDA

PROCEDURE:

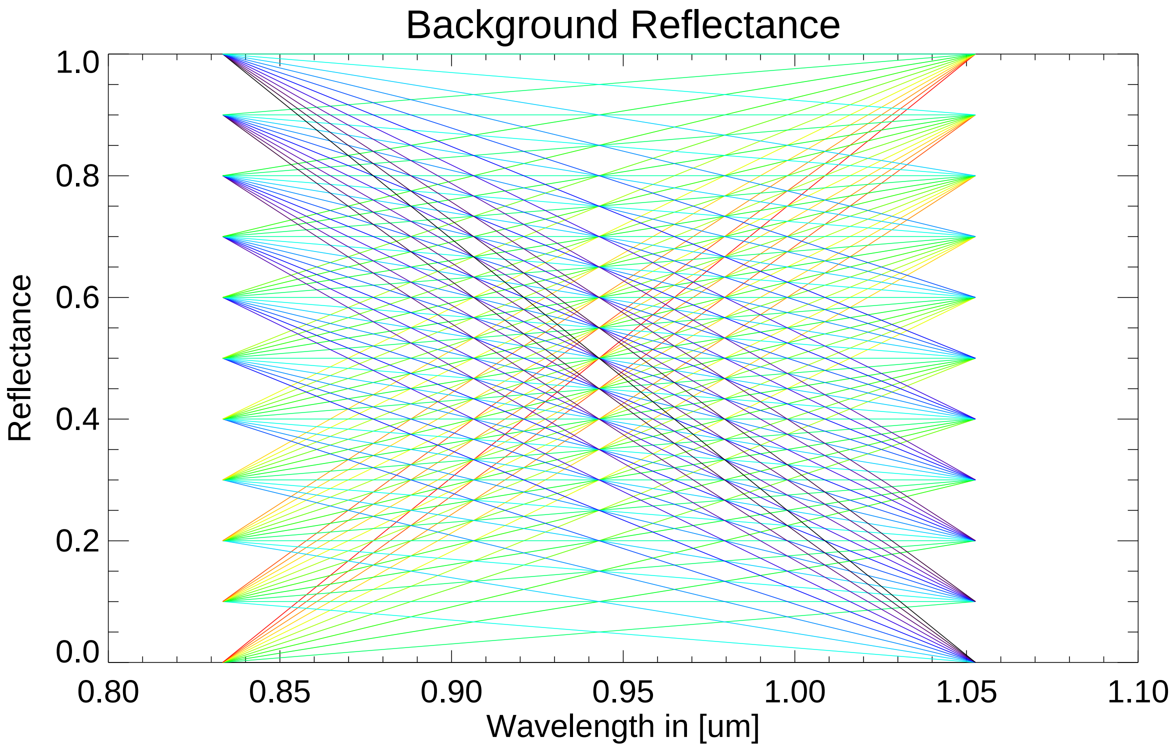
Computed irradiances, transmissions and path radiance (with MODTRAN3 using the DISORT option).

PARAMETERS:

- Atmospheric state was mid-latitude summer,
- Visibility of 23 km,
- Columnar water vapor was fixed at 2.4 g/cm^2,
- Target height was at 0.4 km,
- Sun zenith at 40 degrees and
- Spectral resolution ≈ 1 nm.

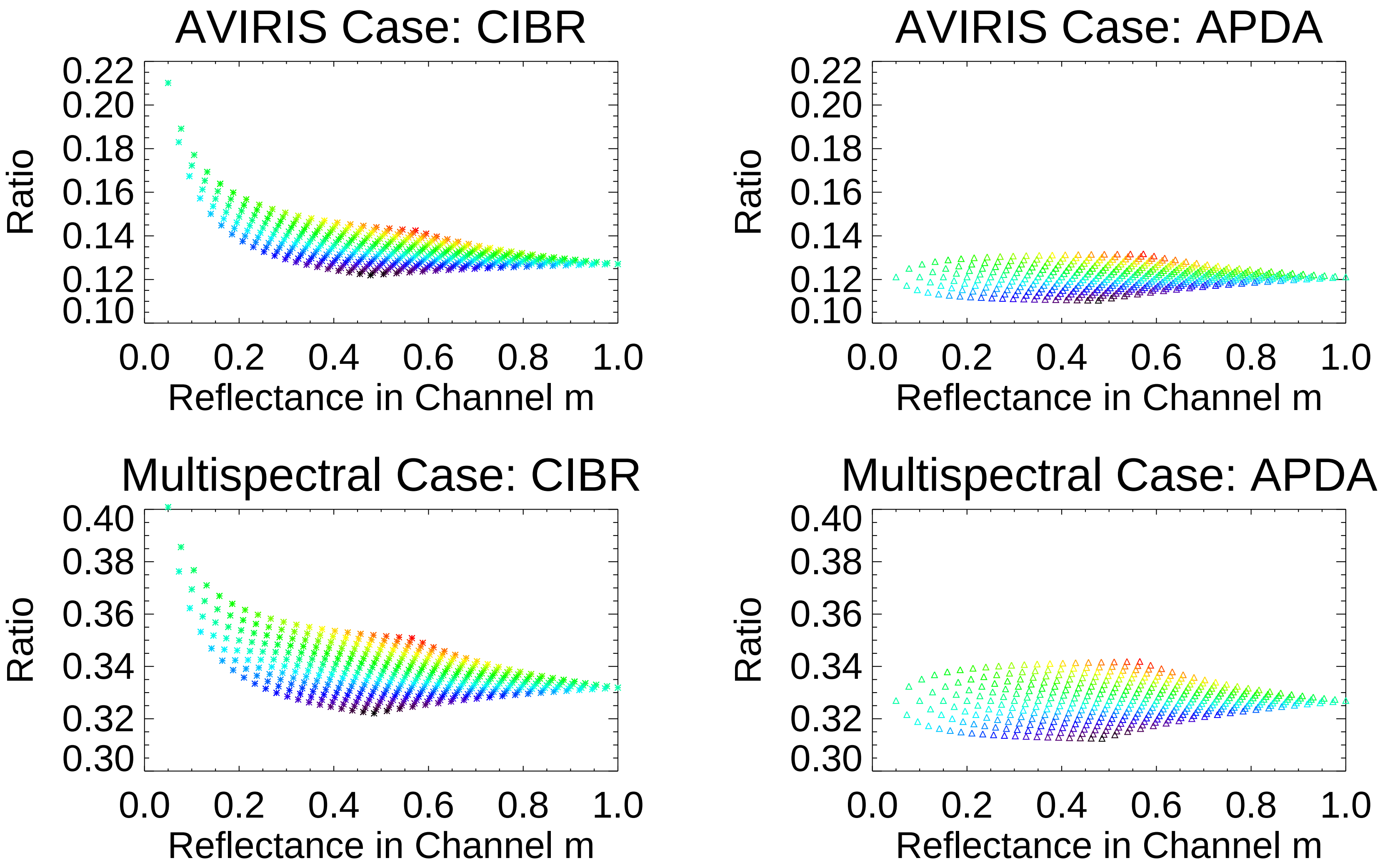
- The ground reflectances $\rho_{g,1}$ and $\rho_{g,2}$ was changed from 0.05 to 1. in steps of 0.05:

$$\rho_g(\lambda) = \rho_{g,1} + \frac{\rho_{g,2} - \rho_{g,1}}{\lambda_{max(r2)} - \lambda_{min(r1)}} \lambda - \lambda_{min(r1)}. \tag{10}$$



Back ground reflectances (color indicates slope).

Channel	AVIRIS Case	Multi-Spectral Case
$r1$	0.869-0.879 μm	0.86-0.89 μm
m	0.936-0.946 μm	0.91-0.97 μm
$r2$	0.994-1.004 μm	0.99-1.04 μm


AVIRIS Case: CIBR

AVIRIS Case: APDA

Multispectral Case: CIBR

Multispectral Case: APDA

Water vapor ratios as a function of band-averaged ground reflectance of channel 2 for a 10 nm bandwidth instrument (AVIRIS) and a multi-spectral instrument using Duntley's model.

BACKGROUND/WATER VAPOR EFFECTS ON CIBR/APDA

GOAL: Test the behavior of CIBR and APDA techniques over spectrally varying backgrounds

SPECTRAL DATA BASES:

- 190 mineral spectra (JPL/Univ. of Colorado)
- 64 spectra of man-made/natural materials
- 125 simulated vegetation spectral data base with variable leaf water content (PROSPECT and radiosity models used)

STEPS:

- Re-sampled spectra at 2.5 nm sampling distance.
- Compute the TOA radiance over the water vapor band centered on 940 nm.
- Vary water vapor amounts from 0.05 to 5 g/cm^2 in 12 steps (only data from 1 to 5 g/cm^2 was used).

- Atmosphere had a constant visibility of 20 km with continental aerosols.
- Target height was set at sea level.
- Sensor located above the atmosphere.

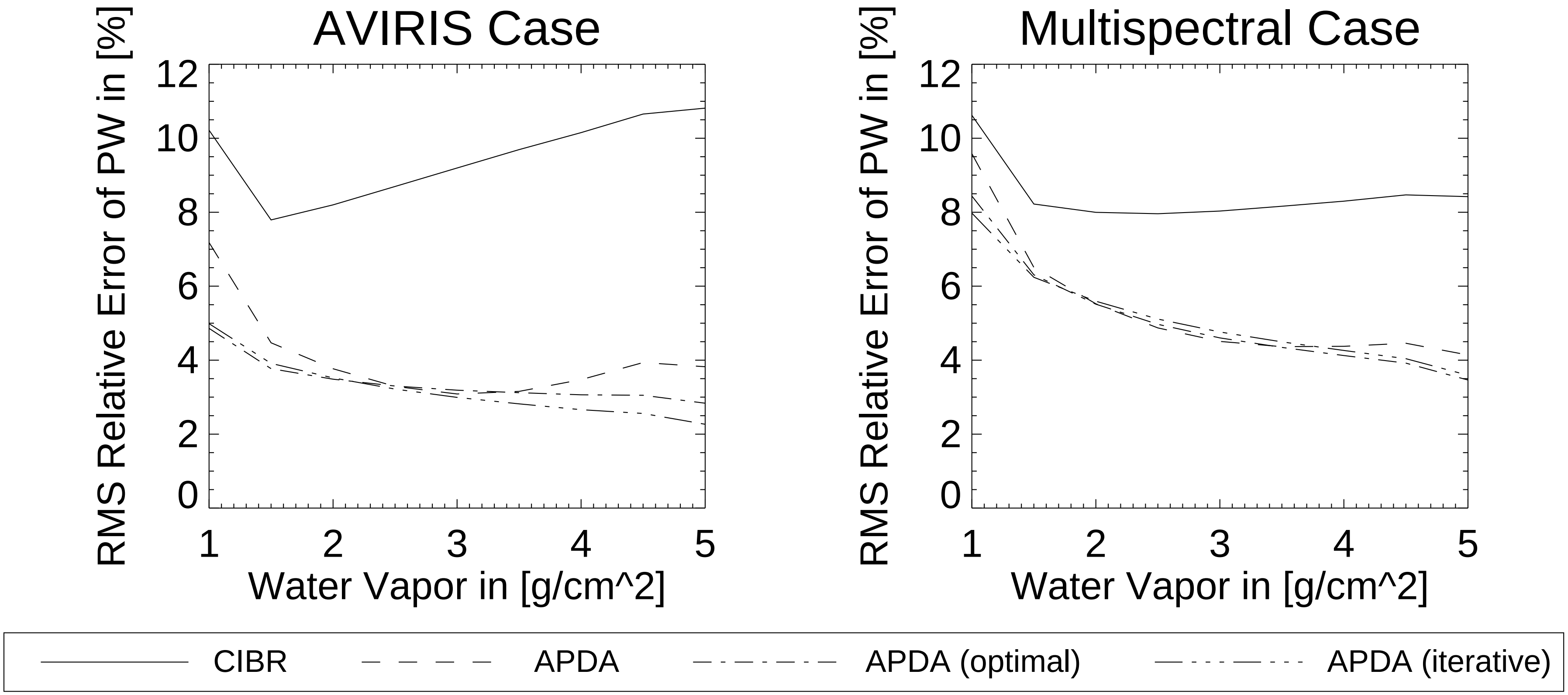
RMS relative error in percent:

$$\varepsilon(PW_j) = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}[\frac{(PW_{j,true} - PW_{i,est})}{PW_{j,true}}]^2}$$

in water vapor for all N =379 reflectance spectra as a function of water vapor.

4 TECHNIQUES:

1. **CIBR**: Original CIBR equation (7).
2. **APDA**: Regular APDA equation (6) using a fixed water vapor amount of 3 g/cm^2 to compute the path radiance $L_{p,m}$.
3. **APDA (optimal)**: Equation (6) with computed water vapor dependent path radiance $L_{p,m}(PW)$.
4. **APDA (iterative)**: Equation (6) with the iterative scheme (5 iterations).



RMS relative error $\varepsilon(PW_j)$ in % in water vapor for all 379 reflectance spectra as a function of water vapor for four different water vapor retrieval techniques.

QUASI SIGNAL TO NOISE RATIO (SNR):

$$SNR(R_x(PW)) = \frac{\overline{R}_x(PW_{min})) - \overline{R}_x(PW_{max})}{\sigma(R_x(PW))},$$

$$\text{where } x = \{\text{CIBR, APDA, APDA(optimal), APDA(iterative)}\}, \qquad (11)$$

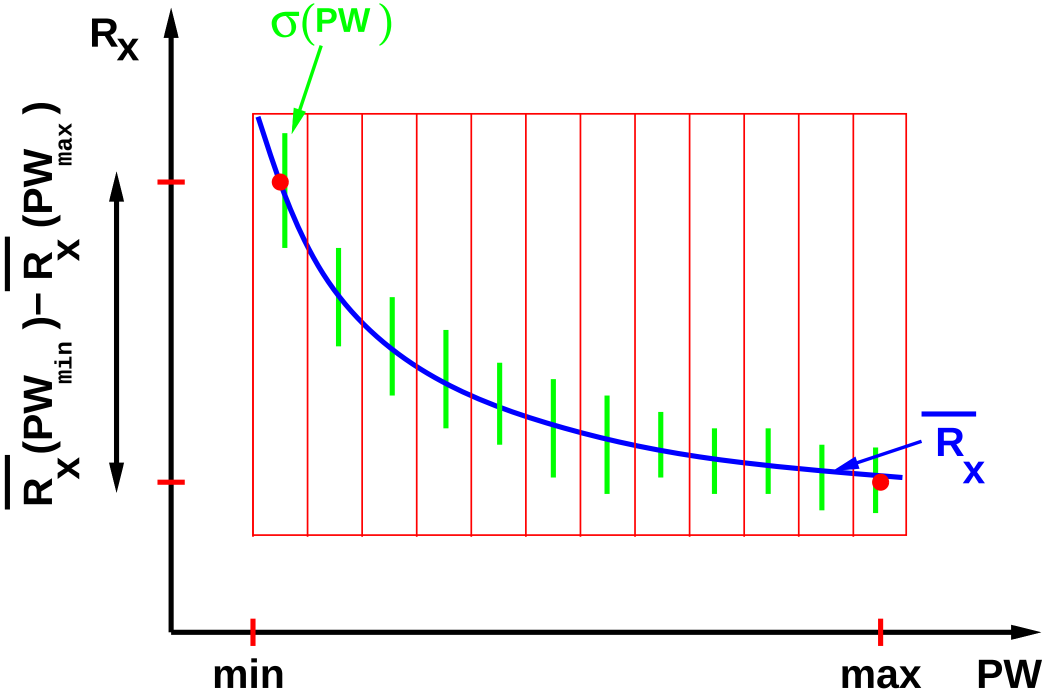
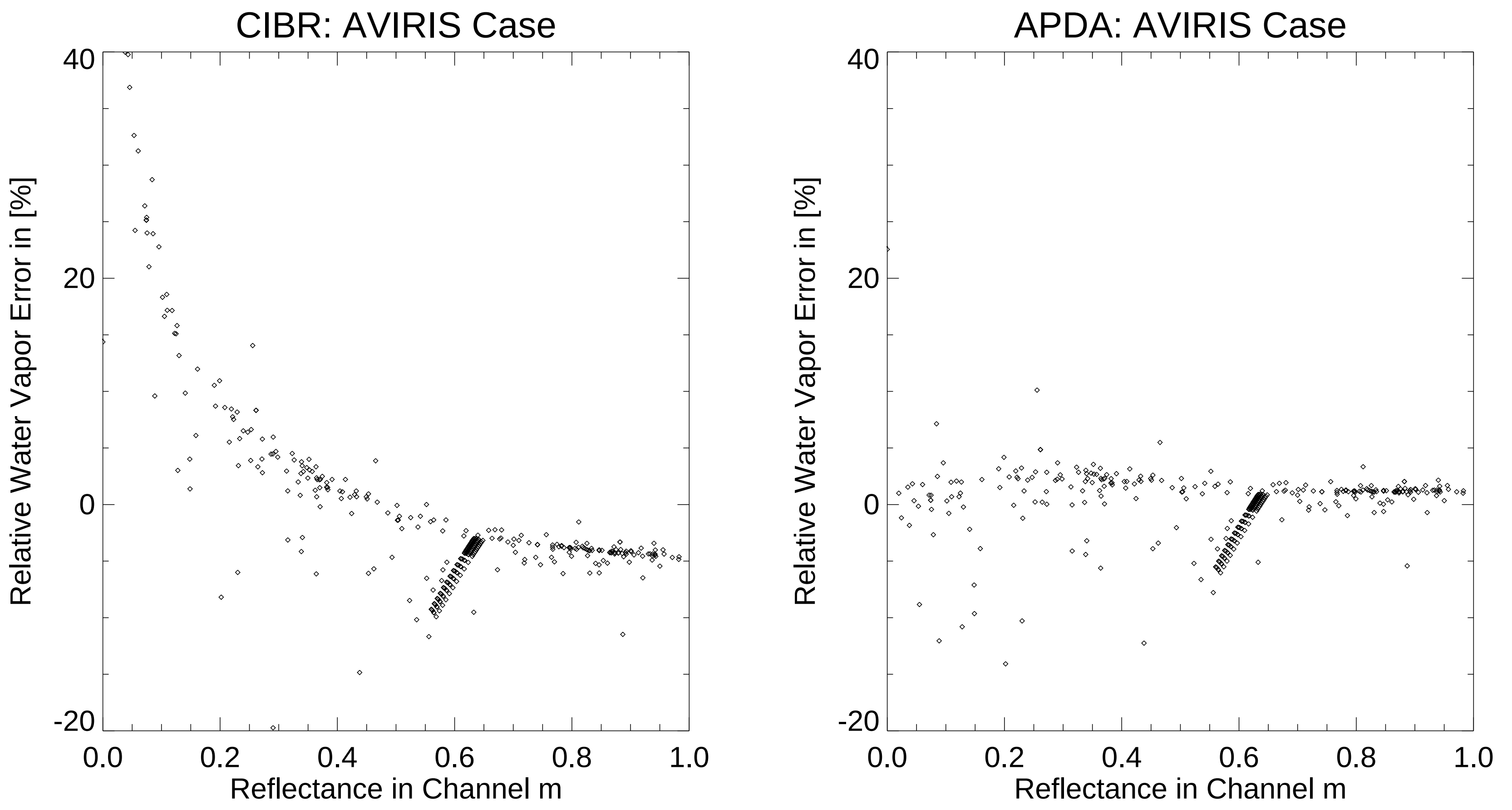

R_X
σ(PW)
$\overline{R}_X(PW_{min}) - \overline{R}_X(PW_{max})$
$\overline{R}_X$
min
max
PW

Table 1: SNR comparison

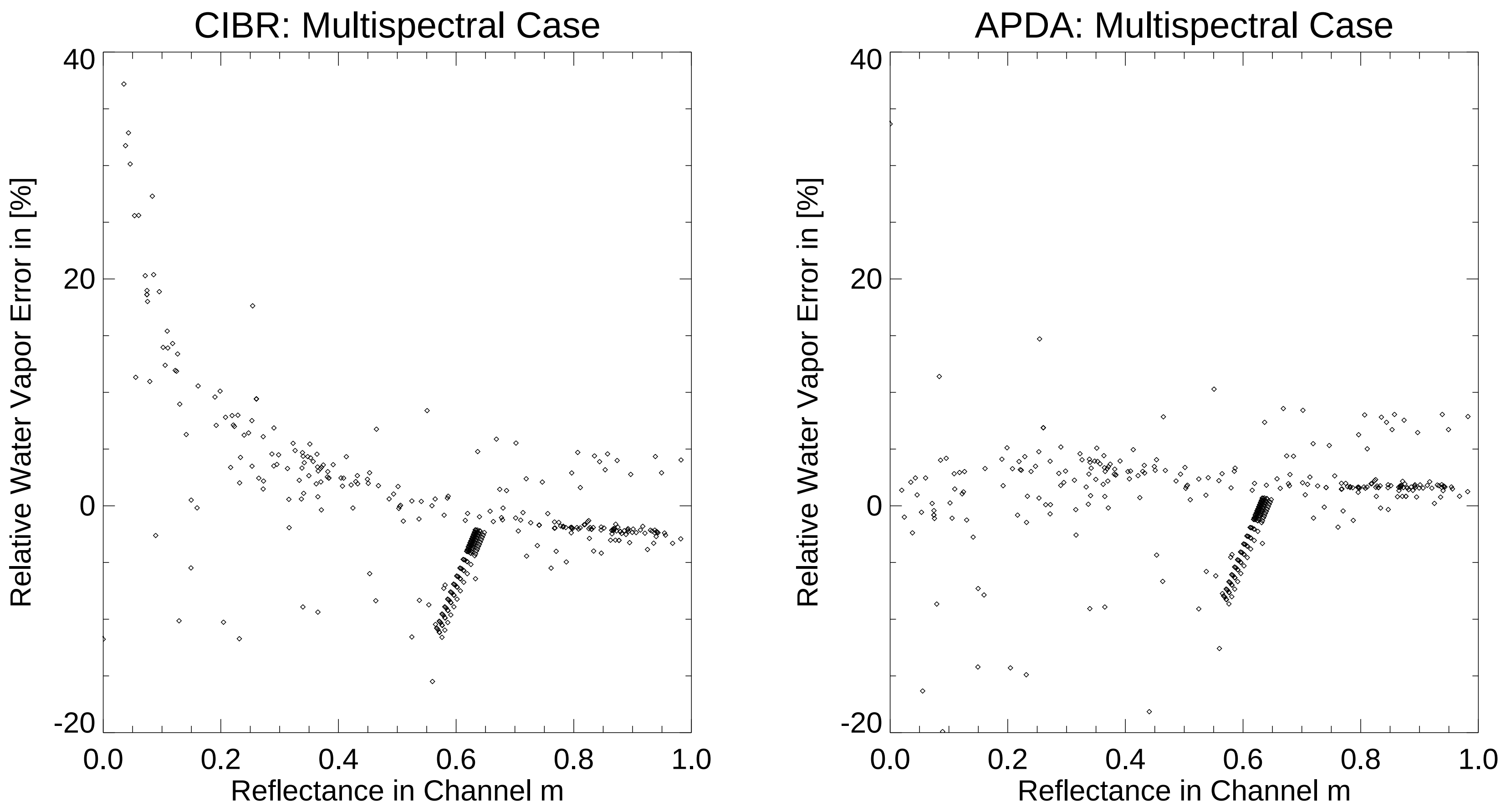
Case:	AVIRIS			Multi-spectral		
Retrieval Technique	Range of R	$\overline{\sigma(R)}$	$SNR_{min/max}$	Range of R	$\overline{\sigma(R)}$	$SNR_{min/max}$
CIBR	0.243	0.01607	14.7-15.8	0.267	0.01511	16.7-17.9
APDA	0.253	0.00604	21.5-58.7	0.277	0.00870	18.4-42.1
APDA (optimal)	0.245	0.00496	30.5-66.8	0.267	0.00789	20.7-50.2
APDA (iterative)	0.246	0.00497	30.5-66.6	0.270	0.00796	21.2-49.7

Table 2: Percentage of reflectance spectra above 5% and 10% RMS Relative Water Vapor Error

Retrieval Technique	AVIRIS 5%	Multi-spectral 5%	AVIRIS 10%	Multi-spectral 10%
CIBR	35.3562	32.9815	9.49868	13.1926
APDA	8.17942	21.1082	1.84697	3.16623
APDA (optimal)	8.70712	20.3166	2.37467	3.43008
APDA (iterative)	7.91557	20.3166	1.84697	3.16623



Relative water vapor errors over 379 backgrounds as a function of band-averaged ground reflectance for a 10 nm bandwidth instrument (AVIRIS). Note the lined up points near 0.6 reflectance are from canopy spectra.



Relative water vapor errors over 379 backgrounds as a function of band-averaged ground reflectance for a multi-spectral instrument. Note the lined up points near 0.6 reflectance are from canopy spectra.

Table 3: Materials with RMS Relative Water Vapor Errors $> 10\%$ (AVIRIS Case)

CUMMINGTONITE-IN-6A (sloped) (non-linear)	ENSTATITE-IN-10B (sloped) (non-linear)
FAYALITE-NS-1A (dark) (sloped) (non-linear)	HEMATITE-FE2602 (sloped) (non-linear)
MOLYBDENITE-S-11A (sloped)	SIDERITE-COS2002 (sloped) (non-linear)
TRIPHYLITE-P-4A (sloped)	

Table 4: Materials with RMS Relative Water Vapor Errors $> 10\%$ (Multi-spectral Case)

ANTHOPHYLLITE-IN-8A (non-linear)	ANTLERITE-SO-11A (sloped) (non-linear)
BUDDINGTONITE-NHB2301	CUMMINGTONITE-IN-6A (sloped) (non-linear)
DICKITE-PS-3A (dark) (sloped) (non-linear)	ENSTATITE-IN-10B (sloped) (non-linear)
FAYALITE-NS-1A (dark) (sloped) (non-linear)	HEMATITE-FE2602 (sloped) (non-linear)
MOLYBDENITE-S-11A (sloped)	SIDERITE-COS2002 (sloped) (non-linear)
TOURMALINE-DRAVITE-S-CS-1A (dark) (sloped) (non-linear)	
TRIPHYLITE-P-4A (sloped)	

CLASSIFICATIONS OF BACKGROUND SPECTRA:

DARK: If reflectance in channel m below 0.1

SLOPED: If

$$R_{slope} = \frac{|\overline{\rho_{g,r1}} - \overline{\rho_{g,r2}}|}{\overline{\rho_{g,r1}} + \overline{\rho_{g,r2}}} > 0.05.$$

NON-LINEAR: $R_{non-linear} < 0.95$ and $R_{non-linear} > 1.05$

$$R_{non-linear} = \frac{\overline{\rho_{g,m}}}{w_{r1}\overline{\rho_{g,r1}} + w_{r2}\overline{\rho_{g,r2}}}$$

CONCLUSIONS

- An efficient technique to determine the amount of columnar water vapor has been derived from a modified radiative transfer equation.
- The technique seems to work much better than the current CIBR techniques which neglect the effects of path radiance.
- We show how the CIBR and APDA behave over dark, bright and spectrally variable backgrounds.
- A large number of mineral, man-made and simulated vegetation spectra were used and the relative water vapor error lies within $\pm 5\%$ for most reflectance spectra.
- A challenge remains to determine water vapor over dark surfaces such as water since the path radiance is now the only quantity containing information about the water vapor.
- More work is also needed to retrieve water vapor in rough terrain.
- The presented techniques may also be useful to retrieve other gases such as CO_2 and O_2.

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